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LIGHTNING AND AIRCRAFT

By G. C. SIMPSON, F.R.S.

(*Revised October*, 1941)

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LIGHTNING AND AIRCRAFT

By Dr. G. C. Simpson, F.R.S.

June, 1933.
Revised October, 1941.

There is always some electrical force in the earth's atmosphere, especially near the surface, but in fine weather this is relatively small and for most practical purposes may be neglected. The electrical field which exists in all regions during fine weather is called the normal field.

As soon as the weather becomes disturbed more intense electrical forces make their appearance. During fog the normal electrical field becomes greatly intensified, and in some cases may become so strong that some electrical discharge takes place from the ends of pointed metallic conductors connected to the earth. If, however, the fog is not accompanied by precipitation, the electrical fields never become sufficiently strong for disruptive discharges to take place and, therefore, fogs in themselves do not produce dangerous conditions.

As soon as precipitation in any form, rain, snow, sleet or hail commences, an entirely new set of electrical conditions is introduced. The exact physical cause of these new electrical forces is not known ; it is possible that there may be several causes acting separately and the following are the most important which have been suggested so far.

A shower of falling particles may act as a great " influence machine," which, working on the small normal electrical field, increases it many times in intensity —many suggestions have been made as to how this may be done, the chief theories being due to Elster and Geitel in Germany, and C. T. R. Wilson in England.

Laboratory experiments have proved that when a water drop suddenly breaks up in the air into a number of smaller drops considerable electrical separation takes place. The water becomes positively charged, while the air becomes negatively charged. When the drops break in an ascending current of air the positively charged water-drops, on account of their weight, lag behind the ascending air which carries the negative charge. This results in the negative charge being removed from the positive charge, the former being carried into the upper part of the cloud and the latter remaining in the lower part or falling to earth as rain. The separation of electricity into different parts of the cloud will set up large electrical fields.

A process similar to the electrification of water when a drop is broken takes place when two solid particles in contact are rapidly torn apart—for example, during the rapid rebound after two particles have collided. When this occurs the solid particles become charged with electricity of one sign while the air takes the corresponding amount of electricity of the other sign. This is true even when the two colliding particles are of identical composition, the process being different from the generation of electricity by friction which necessitates the rubbing of two dissimilar bodies, one of which takes positive electricity and the other negative. A good example of the generation of electricity by collision in the atmosphere occurs during blizzards when the collisions of the snow particles in the air and the violent contacts between the drift snow and the snow on the ground often produce sufficiently high electrical

fields to cause brilliant discharges from earth-connected conducting bodies—the so-called St. Elmo's fire. The same kind of collision between ice particles occurs in the upper parts of a cumulus cloud, especially if soft hail is mixed with ice crystals. The downward fall of the ice particles all charged with electricity of one sign results in a large separation of electricity accompanied by large electrical fields.

It is quite possible that each one of these methods of producing electricity plays some part in the atmosphere ; but for our present purpose it is important to note that the electrical effect is produced after the precipitation is formed and has commenced to fall relatively to the air in which it is supported. A second point to notice is that the air must be moving upwards if any large quantity of electricity is to be developed, and that generally speaking the more violent the ascending currents the more efficient they will be in producing electrical effects. This is because the more rapidly the air rises the greater is the quantity of water vapour which is converted into water or ice and the greater the internal agitation of the air which is necessary to bring the particles —solid or liquid—into contact.

With these considerations in mind it is easy to understand the efficiency of different kinds of weather in producing electrical effects. Commencing with fine weather we have only the normal electrical field which is small and for most purposes unimportant. When fog or cloud is formed, no new electricity is produced and all that they can do is to modify the existing normal field ; but the electrical fields produced in this way are not strong enough to be of much practical interest. As soon as some of the cloud particles become sufficiently large to fall through their neighbours, the possibility of the production of electricity and its separation arises. If the rain or snowfall is slow and steady, as in the case of the precipitation associated with warm fronts when the whole sky is covered with cloud which has a very slow and regular ascent, the production of electricity is slow and the electrical field does not rise to high values although it may be higher than during fine weather. As light rain generally produces an electrical field of the opposite sign to that of the normal field, it often happens that during light rain even the small normal field is reduced in intensity.

When the atmosphere becomes unstable, as at a cold front, or in polar air, or during a hot summer day, the ascent of the air no longer takes place slowly and steadily over a vast area, but tends to occur in local ascending currents each one of which is marked out by a cap of cloud surrounded by clear air. As the ascent progresses and becomes more violent, showers of rain or snow are formed. The conditions are then suitable for efficient separation of electricity. As the ascending currents, and with them the precipitation, become more extensive and more intense, so the electrical separation increases. The accumulation of large electrical charges results in strong electrical fields, and as soon as these fields become large enough electrical discharges commence. The discharges are at first probably small and local, but as the field increases still further the large disruptive discharges which we call lightning take place and we have a thunderstorm.

With still greater increase in the ascending currents, hail is formed and the lightning becomes more frequent and violent. It is well known that hail storms are nearly always accompanied by violent electrical discharges ; it is not definitely known whether the formation of hail in itself is in any way responsible for the production of electricity ; but as it is known that hail stones can only be formed where the upward velocity of the ascending currents is sufficiently great to support the hail stones during their growth, the presence of hail is proof that rapidly ascending currents exist and violent electrical effects may be expected.

We may now summarise what has been said regarding the various weather types and the electrical effects which may be expected to accompany them in the following sequence :—

(a) *Clear sky :* normal fine weather electricity.

(b) *More or less cloud or fog, but no precipitation :* outside the cloud no marked effect on the normal field ; within the cloud or fog local increases of the normal field, but not to any dangerous extent.

(c) *Steady light rain :* the normal field may be increased or decreased but no large electrical forces are produced either within or without the cloud.

(d) *Showery rain, especially from detached clouds :* electrical generation takes place within the cloud and the electrical force may be strong near to the cloud. Electrical discharges are not likely from small detached clouds, but they are not impossible.

(e) *Heavy showery rain :* the electrical conditions become more marked and culminate in thunderstorms.

(f) *Hail or soft hail :* seldom occur without electrical discharges and the most violent thunderstorms are generally hailstorms.

(g) *Snow :* snow is similar to rain in that if it is light and steady there is little electrical effect, while if it falls from shower clouds there may be much electrical activity. The lightning from snow showers is usually infrequent but very intense. In addition, drift snow can give rise to strong electrical fields near the ground.

(h) *Duststorms :* the mere raising of a cloud of dust produces strong electrical fields, but it is not clear whether the lightning discharges which occasionally accompany dust storms are due to the dust or to rain in the upper part of the cloud which fails to reach the ground.

Lightning.—Whatever may be the actual process by which electricity is generated in the atmosphere, the subsequent process is certain. The generation of electricity consists in the separation of positive electricity from negative electricity ; this, however, is not sufficient to produce an electrical field ; for after separation the two kinds of electricity may remain so near together that they neutralise one another at external points. For example, if a glass rod is rubbed by a silk handkerchief, electricity is separated, the positive electricity clinging to the glass rod and the negative electricity clinging to the silk. So long as the handkerchief is about the rod no electrical effect can be produced. It is only when the positive electricity is removed from the neighbourhood of the negative electricity by withdrawing the handkerchief from the rod, that external electrical fields can be set up.

The mere generation of the electricity in the cloud is, therefore, not sufficient ; the negative electricity must be removed from the positive electricity and each kind of electricity concentrated in different parts of the cloud. Formerly it was supposed that a cloud was a good conductor of electricity and, therefore, that the two kinds of electricity could not be present in the same cloud. One, therefore, spoke of a positive cloud or a negative cloud and electrical discharges taking place between "two oppositely charged clouds." We now know that a cloud is almost a perfect non-conductor of electricity, and that two parts of the same cloud may contain very high charges of positive and negative electricity. The picture we now form is that the electricity is attached to the cloud or rain or snow particles and that, as each of these particles is surrounded by non-conducting air, the charge cannot leave its carrier but must go wherever that carrier goes. In this way the different kinds of electricity may become concentrated in different parts of the cloud. For

example, if the positive electricity is attached to the raindrops, while the negative electricity is attached to the cloud particles in an ascending current, the negative electricity will accumulate in the top of the cloud, where the cloud particles are carried by the ascending currents, while the positive electricity will tend to accumulate in the lower part of the cloud where the raindrops are found.

In this way very large quantities of electricity may be accumulated in different parts of the cloud, not necessarily directly above and below one another; but the front of the cloud may have a strong charge of positive electricity while the back part may have negative electricity, and vice versa. The quantities of each of the two kinds of electricity in one cloud may be very different; for the carriers of one kind may have fallen out of the cloud or have been otherwise removed. Observations show that the rain carries away with it more positive than negative electricity, therefore, as a rule there is at any one time more negative than positive electricity in the cloud. The point, however, with which we are concerned is that the electricity is localised and found in definite regions of a cloud. Each concentration of electricity is the origin of an electrical field of force, which is most intense at the edge of the region containing the charge. If the cloud contains only one region of charge then the field is most intense directly under this charge. If the cloud contains two regions of charge of different sign then the field may be most intense either between the two charges or directly under one of them. As the electrical strength of the air breaks down where the field is the most intense and from this point a lightning flash starts, we see that a flash may start within the cloud and pass from a region of positive to a region of negative charge all within the cloud; or it may start under one charge—but well within the cloud—and pass from there to the ground. This is a radically different conception from the old one which assumed that a cloud was a conductor and that all lightning discharges started on the outer boundary of the cloud and passed either to the ground or to another disconnected cloud. There are reasons to believe that the discharges entirely within the cloud are more frequent, but less powerful, than those which pass out of the cloud and reach the ground.

The presence of an aeroplane may affect an electrical discharge in two ways. Before an electrical discharge can start the electrical force must reach that intensity which breaks down the air. If into a part of the electrical field which is near but slightly below the sparking value an electrical conductor is introduced the conductor concentrates the field and may raise the intensity above the sparking value. A discharge then starts at the conductor which may develop into a lightning discharge. If, therefore, an aeroplane flies near to that part of a cloud which carries a high charge it may initiate a lightning discharge.

The second way in which an aeroplane may influence a lightning discharge is to be by chance near to the path of a discharge which has started elsewhere. When a discharge starts at any point it first builds for itself a conducting channel through the air. The general direction of propagation of a discharge is towards the electricity of the opposite sign to that which caused the breakdown. Thus if a discharge starts in a region of the cloud which has a positive charge the channel will grow either towards the negative electricity in another part of the cloud or to the negative electricity induced on the surface of the ground; but the actual path traversed is a matter depending on the ever-changing conditions at the tip of the channel as it progresses. If there is a highly conducting path—such as the metal in an aeroplane—within striking distance of the channel as it lengthens, the channel will be attracted to this and pass into it at one end and out at the other. What is meant by striking distance cannot be stated in exact terms. It will depend on how much help the conductor will give in shortening the air path. The greater the distance which a conductor extends in the general direction of the electrical field the

greater will be the attraction. As the majority of flashes below a cloud strike downwards to the earth, the air path may be appreciably shortened by a trailing aerial. Generally speaking, the greater the linear length of a conductor the more risk there is of its providing a short circuit for a lightning flash. Thus the long wire used in towing targets by aeroplanes may provide an attractive path for a discharge even though it lies in a horizontal direction; for the electrical field is by no means always vertical.

In practice it is impossible to separate these two effects of an aeroplane and say whether a plane was struck because it initiated a flash or because it attracted a flash started elsewhere. All that we know is that the plane has been struck; even eye-witnesses cannot say whether the flash started at the plane or struck it from above or below. The channel of a flash is as a rule completed well within a thousandth of a second, which means that the eye could not follow the direction of formation. As, however, the region in which there is the greatest chance of starting a flash is the same as the region in which there is the greatest probability of meeting a flash, the difference has little practical significance. The conclusion to be drawn is however clear; the aeroplane should, if possible, avoid the regions where there is great electrical activity. As already explained, these regions are the parts of the cloud where the most violent ascending currents occur and are generally situated some distance within the cloud itself. If, therefore, an aeroplane is caught in a thunderstorm it would be best from the point of view of both dangerous electrical discharges and dangerous vertical air currents to fly well below the cloud and never through it, if that can be avoided.

Danger and Protection.—A lightning flash is a rapid unidirectional flow of electricity along an ionised channel formed in the air by the discharge itself. When we say a body has been "struck by lightning" we mean that that body has formed part of the path along which the electricity has flowed. No body can be struck by lightning which is unable to carry an electric current. A bad conductor will carry part of the discharge, the remainder continuing through the air, mainly along the surface of the poor conductor. As the air channel carrying the current is at a high temperature this may result in burning if the surface consists of an inflammable material. A good conductor carries the whole of the current and the effect of the discharge can easily be determined. The current in passing through the conductor being unidirectional obeys Ohm's law, and, therefore, the potential between any two points of a conductor while it is carrying a lightning discharge is simply the product of the current and the resistance between the two points. In the same way the heat generated in the conductor is the product of the square of the current, the resistance and the time.

A typical lightning flash carries 100 coulombs of electricity and lasts for 0·001 second. If this is passed through an iron rod having a cross sectional area of one-fifth of a square inch (a round wire of diameter half an inch) the temperature of the wire will not be raised to the boiling point of water and, therefore, the rod will be in no danger of melting. If the rod is divided into a number of strands the effect is the same so long as the sum of the cross sectional areas of the strands is equal to that of the rod. While the current is passing the drop of potential along the rod will be approximately 5 volts per inch; therefore, the maximum difference of potential in 5 feet—the linear dimension of a man—would only be 300 volts which, considering the short period of the current, cannot be dangerous.

No matter what may be the dimensions of a good conductor it will endeavour to take the whole discharge, and passing a large current through a thin conductor leads to high temperature and ultimate fusing. A thin conductor has as great

an attraction for a lightning discharge as a thick one of equal length; but while the latter conductor may be able to pass the whole discharge with safety the former will be dangerous in that it attracts the discharge to itself then on fusing leaves the discharge to find its own way, with possible disaster to surrounding objects.

If an aeroplane, without an aerial, is near to a lightning discharge it has not a very great attractive power, because its linear dimensions are not great. If, however, it is struck the discharge will enter and leave at those points which give the longest path in the direction in which the discharge is travelling. The actual direction of the field will determine the exact points in each individual case, but experience shows that they are most commonly the tips of the wings, the nose of the plane and the end of the tail. If all these points are connected together by one or more metallic paths, the total cross section of which is of the order of half a square inch, the flash can enter and leave the plane without doing any damage. In most planes there are sufficient metal paths to satisfy this condition, but in machines largely built on wooden frameworks there may be some section in which the metal paths are only meagre and a structural wire or a control wire has to take a heavy load, and there is then danger that this member may be burnt out. The more metal there is in the framework of the machine the less the danger of this occurring. It is clearly desirable that the current should have open to it every possible path between the point where it enters and the point where it leaves, so as to decrease the resistance and to increase the effective cross-section of the conducting path. This will only be attained if every piece of metal in the aeroplane is bonded *at both ends* to other metal conductors.

On machines without aerials there is practically no danger to the personnel, for the cockpit is generally situated within such a mass of metal that there is little chance of any part attaining a high electrical potential relatively to any other part, so that there is little tendency for the discharge to pass into the human occupant.

The position, however, is much more serious if the machine has a trailing aerial. In the first place the aerial extends the linear dimensions of the conductor and generally in the direction which the flash wishes to take. Thus a machine with an aerial is more likely to be struck than one without. Further the aerial goes directly into the cockpit, and is not directly connected to the main mass of bonded metal of the aeroplane which takes the place of a normal "earth." This will conduct the high potential current of the flash right into the interior of the plane and through the numerous "leads" of the wireless set into dangerous proximity to the wireless operator, and to anyone wearing headphones. The most important thing, therefore, to be done when it is known that the plane is in a danger area, or is about to enter a danger area, is to withdraw the aerial. It is not sufficient just to "earth" the aerial, for this does not reduce the attraction which the aerial exerts on a near discharge, or the tendency to initiate a discharge. Also an earthed aerial is almost certain to be melted if the plane is struck. The aerial should always be earthed before the operator commences to wind it in, otherwise he will be in considerable personal danger if the plane is struck while he is handling the winch.

The wireless operator can assist the pilot in deciding when dangerous conditions exist by noting any considerable increase in the number or strength of atmospherics. He should inform the pilot, who will consider this information together with the weather conditions in the region towards which he intends to fly. If the pilot considers it desirable, he will order the wireless operator to earth and wind in the aerial. The pilot should endeavour to issue this instruction

in plenty of time for the aerial to be wound in before the real danger zone is reached. If the danger zone—characterised by heavy rain, hail, snow or lightning—is reached before the aerial can be wound in, the aerial should be immediately earthed and the aircraft flown out of the storm as quickly as possible, even if that necessitates flying back on its course. As soon as conditions allow the aerial should then be wound in, when the pilot will be in a position to consider whether or not he should proceed on his course through the storm.

When an aeroplane is struck by lightning the danger is very real but it is easy to over-rate it. As a matter of fact, no authentic case is on record of an aeroplane having been wrecked as the result of being struck by lightning. Moreover the number of cases is extremely small. The first report of a British aeroplane having been struck by lightning was made to the Air Ministry in January, 1925, and between that date and June, 1933, only ten cases have been reported. In no case has a death resulted and in every case the machine has made a safe landing. A short account of each of these occurrences is given in Appendix I, and a study of these will show that while to be struck by lightning is not without its danger and excitement it is far from being so disastrous as is generally supposed.

So far we have only considered the effects of the disruptive discharges in the atmosphere which take the form of lightning. There are, however, effects due to the electric field which are not connected with lightning and these are usually described as static charges and static discharges.

Static Discharges.—We have already stated that when an aeroplane is flying in a strong electric field it tends to concentrate the electric force. This concentration is particularly great on all protuberances such as the nose with the propeller, the tail with its fins, the wing tips, the supports of the fixed aerial and, above all, the trailing aerial. At all these points the field may become so strong that the first stage of electrical discharge sets in. This takes the form of a " brush discharge " which in other circumstances is called St. Elmo's fire. The brush discharge indicates that electricity is passing from the plane to the air, and if the field is not too strong the electrical tension is thereby reduced. If, however, the field becomes very strong the brush discharge may pass into a spark discharge, which, as already explained, may develop into a lightning discharge. There is practically no danger in a brush discharge itself, but it is a sure sign that the plane is in a region of abnormal electrical tension. Its presence is therefore more of a warning than a danger. The light from a brush discharge is feeble and cannot be seen in full daylight ; but at night it often appears sufficiently bright to cause apprehension, and observers have spoken of the interior of a plane being lit up by the intensity of the brush discharge. It should be stressed, however, that brush discharges never occur within a plane, they are always on the outside.

A brush discharge being an intermittent electrical current sets up electrical oscillations which produce a crackling noise in a wireless receiver, hence the use of the wireless becomes difficult if not impossible when there is much static discharge taking place from the plane.

Static Charges.—If all the metal in an aeroplane is properly bonded there can be no differences of potential within the plane. If, however, there are a number of metal pieces not all bound together these will take up different potentials and shocks may be experienced when these metals are touched. An example of this kind of experience has been reported from India (59628/30). On August 21, 1930, a Bristol Fighter was flying over the Attock district when it encountered a rain storm. After passing through the storm the wireless operator was attempting to use the W/T apparatus and was wearing headphones, when both he and the pilot experienced electric shocks. The pilot received shocks

when he touched any metal part of the aircraft, or when he held the grip of the control column, which is bound with cord ; while the W/T operator experienced a general feeling of shock whether he was touching metallic parts of the machine or not. In this case the aerial was in use and therefore at an entirely different potential from the rest of the machine. Slight shocks of this kind may often be experienced when a machine is flying in a region where the field is very strong ; they are never likely to be dangerous, but they may be distinctly unpleasant.

In a similar way the aeroplane as a whole may become charged when flying through an intense electrical field, owing to the induced charges escaping through local brush discharges or even through the exhaust gases of the engine. Any such charges are rapidly dissipated as soon as the machine flies out of the electrical field ; for the engine exhaust then acts as efficiently as a charge dissipater as it had previously acted as a charge collector. If, however, the machine lands while still in the intense field it may cause a spark on landing, as exemplified in the following case reported as having occurred in 1932 at Crete : —" Some hail had been flown through on this flight and after alighting we were told by two people, who had witnessed the landing from a vessel on the water, that a flash of static at least 3 feet long passed between the hull of the aircraft and the surface of the sea ". Discharge of this nature due to static electricity can never be of the intensity of lightning discharges, for the charge involved is limited by the electrical capacity of the machine and the relatively low potentials associated with brush discharges. They must be extremely rare for the case just referred to is the only one of which there is any record.

Magnetic Effects.—When an aeroplane has been struck by lightning it is generally found that the compass has become deranged and has errors often amounting to over 100°. Examination shows that these errors are not due to damage of the compass itself but to the magnetisation of iron and steel in the neighbourhood of the compass. This magnetisation is the result of the very high electrical currents which flow through all metallic parts of the machine when struck by lightning. It was long thought that a lightning discharge consisted of an oscillatory current, but the magnetic effects produced by lightning strokes prove that the current is not alternating but a simple flow in one direction. In several reported cases of aeroplanes being struck by lightning the engine has failed or become irregular and this is probably due to demagnetisation of the permanent magnets of the magnetos, although so far as is known this has not been actually proved by a subsequent technical examination of the magneto magnets themselves.

So long as the iron and steel in the fuselage of an aeroplane is magnetised the compass is affected, and if the magnetised part is movable and near to the compass, the compass becomes erratic and subject to large variable errors. If the magnetised parts are not movable they can be corrected for by the use of suitable corrector magnets, but as the magnetism of the affected parts is not permanent and tends to be " shaken out " the compass needs constant re-adjustment. It is therefore desirable after an aeroplane has been struck by lightning to remove the residual magnetism. A successful method of doing this without dismantling the aeroplane has been devised and used at the R.A.E., Farnborough. The method consists in wiping all the affected parts with the poles of an electro magnet fed by an alternating current. Several aeroplanes have been demagnetised in this way with very satisfactory results.

Airships.—The risks due to lightning experienced by an airship in flight are of exactly the same nature as those run by an aeroplane, namely, the risk of initiating a flash in a field near to the sparking intensity and the risk of being sufficiently near to the path of a discharge to attract it to itself and so become

part of the discharging channel. In the case of the airship, however, the risk is somewhat greater, because of its greater linear dimension. It has also been frequently stated that there is the added danger that the lightning discharge would ignite the gas in a hydrogen filled airship. It must be admitted that the inflammable gas does constitute an additional risk, but it is much less than has been generally supposed. As a matter of fact it is probable that an airship is actually less vulnerable to a lightning stroke than an aeroplane. This is because the metal framework is so massive that it can pass the most powerful lightning current without any danger. It was stated above that a cross-sectional area of one-fifth square inch of iron would safely carry a lightning discharge while the cross-sectional area of the members of the frame of an airship is much greater than this. There is, therefore, little risk of any high temperature being generated away from the immediate neighbourhood of the actual spots where the discharge enters and leaves the ship.

When R.101 was being designed a small committee examined very thoroughly the problem of the protection of this great airship from the risks of lightning. The report of this committee is reproduced as Appendix II, as it contains a number of technical points which are of interest. The main conclusion, however, of the committee was that the risk of damage due to lightning is not great, and as a matter of fact while on several occasions electrical discharges have quite clearly been observed to strike an airship, to pass through the hull of the ship and out again, there is no properly authenticated case of a rigid airship having been destroyed by the effects of atmospheric electricity.

Kite Balloons.—The problem of protecting a kite balloon from atmospheric electricity is of an entirely different nature from that of the protection of free-flying aircraft. This is due to the fact that the cable at the end of which the balloon is flown is of necessity a metallic conductor. This conductor must always be at zero potential because it is attached to the ground at its lower end. Even in fine weather the normal potential gradient in the air is of the order of 100 volts per metre, therefore the potential in the air surrounding a kite balloon flying at say 1,000 feet is of the order of 30,000 volts. Thus there is a difference of potential of 30,000 volts between any conducting surface attached to the upper end of the cable and the surrounding air. This difference of potential may well rise to several million volts if the balloon is flown in the neighbourhood of a thunderstorm. Differences of potential of this order give rise to brush discharges. A brush discharge from a metal conductor is not dangerous unless it is situated where gas from the balloon can bathe it—for example, near a valve. If, however, the balloon is wet, the surface of the fabric will be a conductor and a brush discharge may form on the wet fabric surface. The electric currents going to supply these brush discharges may set the fabric on fire in spite of its being wet. For a time it was considered that a kite balloon could be protected by arranging metallic "dischargers" at places where brush discharges were likely to form. It is doubtful, however, whether such "dischargers" are really effective; for a discharger does not reduce the difference of potential, and the full difference of potential would continue to exist between the air and every part of the balloon in conducting contact (and when the balloon is wet every part is a conductor) with the cable no matter how many dischargers were fitted to the balloon and its rigging. It is true that a discharger protects the fabric in its immediate neighbourhood and other parts of the balloon may be partly protected by the stream of ionised air which passes down wind from the discharging point; but the whole surface cannot be protected in this way. Experience has shown that in fine weather there is really very little danger of a kite balloon being destroyed by brush discharges. The danger only occurs on the approach of bad weather.

The cable of a kite balloon is equivalent to a very efficient lightning conductor and, therefore, if a thunderstorm approaches there is considerable danger of the cable being struck and melted. Also the wind conditions accompanying a thunderstorm are dangerous to a kite balloon. Formerly, as a protection against atmospheric electricity, metal strands were introduced into the harness of a kite balloon and metallic leads connected the harness to the valves and other exposed parts, but these proved in use to be very troublesome when folding and packing the balloons, and in recent designs of manned kite balloons all such metal parts have been omitted, no special protection being made against atmospheric electricity. This policy seems to be justified because it is extremely doubtful, both on theoretical and practical grounds, whether these are any protection during fine weather: and manned kite balloons are not used when the clouds are low or there is danger of thunderstorms.

APPENDIX I—REPORTS ON AEROPLANES STRUCK BY LIGHTNING

I—Seaplane struck by Lightning between Southampton and Guernsey on January 23, 1925. (571469/25.)

Pilot's report.—" On January 23, while flying from Southampton to Guernsey, I encountered a heavy hail storm about 40 miles south-west of the Needles at 10.50 hours. It was impossible to circumnavigate this storm as it extended for some miles on either side of my course, and I decided to fly under it as I could see bright sunlight on the far side showing that the passage through it would be of only short duration.

" Owing to the noise in the receiver and to guard against accident I switched off the R/T remote control and locked it; omitting to pass Position D to Calshot as scheduled at 10.55. At 11.10 in a short lull in the storm I passed Position E to Guernsey and this message was received by Calshot correctly.

" At 11.15, in spite of the fact that the remote control switch was locked in 'off' position, a blinding flash occurred accompanied by an explosion and a deafening noise in the telephone.

" I recollect seeing showers of red-hot copper globules flying about the cockpit, but do not remember much till I pulled myself together to realise that I had lost most of the 2,000 feet at which I had been flying. The altimeter showed about 200 feet. I set the machine back on its course, looked back at the engine to ensure that all was in order, and sprayed the charred woodwork with pyrene as a precaution. I then pulled out my telephone plug and wound in my aerial, only to find that it had fused off about 6 feet from the inner end.

" Guernsey was reached at 12.08 without further incident.

" On examination it was found that the aerial ammeter had been burnt out, the glass and metal dial having been burst out with considerable force. The aerial connection from ammeter to fair-lead was fused, and an arc had occurred between the winch and the reactance control and then to earth by way of the bowden casing. The gap of this arc was at least 5 inches, and the woodwork and paint in the neighbourhood was badly charred.

" I personally suffered for some hours after this incident from feeling of vertigo."

Inspection report.—" The aerial which was out at the time of the above occurrence has been burnt off at the outer end of the fair-lead, only a short length remaining with small globules of copper adhering to the burnt end. The wire from the fair-lead back to the ammeter and thence to the switch has been burnt between the fair-lead and the ammeter, and the ammeter entirely burnt out, but beyond this point no damage appears to have been done to the set.

" On the underside of the wing tip of the top port plane the fabric has been torn open for about 3 inches square in one place and for about 1½ inches in another. In the case of the larger tear there appears to have been an electrical discharge from the head of a brass screw in the 3-ply of the leading edge, also through a small blackened hole in the 3-ply itself. This screw appears to be in contact with the bonding. In the case of the small tear on the extreme wing tip there has been a discharge from the bonding strip itself into the atmosphere. This strip lies immediately below the fabric, and there are signs of a blackening of the fabric in the immediate vicinity of the strip."

Remarks.—It is clear that in this case the lightning discharge made use of the long metallic path available to it extending from the tip of the top port plane to the end of the aerial. If the aerial had not been out the attraction of the plane would have been much less and the discharge might not have struck the plane. If the aerial had been " earthed," that is, connected to the main mass of metal in the plane, the discharge would have passed down the aerial, and although it would have melted it there would have been no destruction of the wireless apparatus and no shock to the pilot.

II—Seaplane struck by Lightning at Sea near Malta on February 3, 1925. (576135/25.)

Pilot's report.—The pilot of the machine reports that whilst endeavouring to fly through a particularly big rain squall coming from westward at a height of 3,000 feet :—" I was crossing the Island in a south-west direction when the squall became very dense and completely blocked all view of the sea and land. When in a position which I estimate to be above Chirco, a blinding flash came from the propeller, accompanied by a small explosion. The flash was a brilliant white in colour and temporarily blinded me, but I experienced no shock.

" Simultaneously the engine cut right out but the propeller remained turning. I was under the impression that there had been a breakage in the engine. I was not aware that there had been an explosion in the rear cockpit. When I landed I found that an explosion had taken place in the W/T equipment. The port side and bottom of the fuselage were

blown out, including a side strut. Most of the W/T gear had disappeared. Parts of the fabric and a portion of the struts were charred. A rough examination of the engine showed no signs of mechanical breakages. The port cowling showed fuse markings. The metal tipping of one blade of the propeller was twisted and the blade had five or six charred marks across it."

Observer's report.—The observer in the machine reports that :—" Whilst flying through a heavy rain and hail squall, nothing being visible except cloud, the W/T Exercise was progressing satisfactorily, when suddenly at 11.00 hours there was a flash and a loud explosion in the observers' cockpit, and the engine simultaneously cut out. On examination it was found that a side strut just abaft the aerial reel had been blown out, the fabric round it and that at the bottom of the fuselage, together with part of the wooden deck being torn away. The aerial reel, aerial, most of the listening-through key, and the field regulator were blown through the side of the fuselage. The wireless panel was also completely smashed.

" After landing it was seen that the metal reinforcing strip around the leading edge of one blade of the propeller was jagged in about six places, and there were charred lines running across the blade at right angles to the edges."

W/T operator's report.—The W/T operator in the machine reports that :—" At 10.55 I noticed that atmospherics were very bad indeed and that reception became extremely difficult. Because of this I looked about and found that we were entering a thick bank of clouds which developed into heavy rain and squalls of hail. The observer was transmitting spots up to 11.00 when there was a loud explosion in the W/T cockpit. I observed a flash followed by a cloud of smoke ; this flash blinded me for the moment and little bits were blown into my face. I noticed that the engine had stopped. I looked at the wreckage and found that the whole aerial reel except for the bush and a few turns of wire was completely blown away. The dexine tube was also gone. Inspecting the panel I found that the L.T. key, field regulator, were blown to pieces ; the majority of the pieces went through the side of the machine. Everything on the panel had a charred appearance. The receiver and transmitter were both badly damaged and charred. The deck from the dexine tube, 6 inches inboard to 2 feet aft, was torn away. The deck had also a charred appearance.

" We landed and I noticed immediately that half the propeller was burnt in about six places across the blade."

Inspection report.—" The propeller had five burns on the leading edge of the one blade and the brass was torn back. One strut was blown out of the side of the fuselage, and there was a large hole blown out of the bottom of the back cockpit, through which could be seen the remains of the wireless gear which appeared to be wrecked. There were signs of singeing on the fairing forward of the pilot's windscreen, and there was a black patch around the switches in the pilot's cockpit as though they had been burnt out. The fabric round the back cockpit showed no signs of burning, but was simply ripped open."

Remarks.—There can be little doubt that in this case a violent lightning discharge entered the machine in the neighbourhood of the propeller. The aerial was out and not earthed ; in consequence the full discharge was conveyed into the W/T cockpit. The violent explosion was due to the normal disruptive action of the high potentials which accompany a heavy electrical current. The remarkable fact that although the W/T operator and the observer were wearing headphones they experienced no electrical shock, is no doubt due to the fact that there is no direct path through a wireless set between the aerial and the headphones. The cutting out of the engine may have been due to a number of causes, but probably was due to damage to the magneto or its leads.

III—Passenger Aeroplane struck by Lightning on April 17, 1926. (685924/26.)

Pilot's report.—" I was piloting a passenger aeroplane on April 17—the wireless apparatus on this machine being completely out of action from various causes I did not attempt to let the aerial down. The clouds were low, somewhere in the neighbourhood of 500 feet ; it was raining and was very rough. Occasional flashes of lightning could be seen in various directions.

" I decided to climb through the clouds, of which there were ten-tenths, hoping to get to calmer regions above. I had been climbing for some twenty minutes through unbroken cloud and was some twenty miles south of Poix at between 4,000 and 5,000 feet, and flying in very heavy snow when I found, for some totally inexplicable reason, that the compass was becoming completely unreliable and that I was apparently flying first west and then east. Fortunately the turn indicator was working satisfactorily and I was enabled to a large extent to disregard the compass on this account.

" Suddenly, without any warning, a very loud report occurred and a flash of lightning so far as I could see, cleared the leading edges of the port top and bottom planes by about 2 feet. A very strong blast of air came from the cabin through the little window behind the pilot's head into the cockpit. So strong indeed was this that various small pieces of

wooden beading were ripped clean off and blown into the cockpit. Several results immediately obtained—the compass continued to be totally unreliable; the port engine cut out a few seconds and continued to miss at first badly and then to a decreased extent for the next hour.

"On landing it was discovered that either the main or an auxiliary flash had struck the port top plane just behind the front spar and had charred the spar to a certain extent and had fused the earthing wires and cables in the immediate vicinity. This included the lead to the navigation light which travels along the front of the spar and which was burnt away for a distance of 4 or 5 inches. The fabric had been ripped from the front spar to the trailing edge on the top side for a width of about 12 inches, and fabric had been burst downwards behind the front spar on the bottom side. The port lower aileron, the trailing edge of which is formed with aluminium tube, had been struck in three places and the metal had been fused, as the result of which the aileron was very badly buckled and the trailing edge had been bent inwards to a considerable extent.

"Control of the machine in the air had been good at all times."

Engineer's report of examination.—"*Port top plane.*—Front spar was struck at junction with wing tip compression strut—the steel fitting at this point was uninjured but the bonding strip and two of its fixing staples were fused and the top face of the spar had sustained two small burns. The fabric of both top and bottom surfaces was split at the front spar from one rib to the next and along the ribs to the rear spar, and the resulting strips of fabric had trailed astern during flight—it is to be noted that the split on the top face of the spar followed the path of the bonding wire. Two struts in one main rib were also broken.

"*Port bottom aileron.*—The fabric was scorched and ripped—a panel extending across three ribs and from the rear spar to the trailing edge was torn from the upper and lower surfaces, one rib was destroyed and another slightly damaged. The trailing edge—of $\frac{1}{2}$ inch diameter aluminium tubing—was fused in three places but not parted: at one point there was a hole in the wall of the tube $\frac{3}{4}$ inch by $\frac{5}{16}$ inch, at the second the hole was $\frac{1}{4}$ inch diameter, and at the third the hole was $\frac{1}{2}$ inch by $\frac{1}{4}$ inch; the first was about the middle of the length of the aileron, the second about 1 foot nearer the tip, and the third on the bend just in front of the rear spar."

"*Damage to compass.*—The compass was sent to the makers for examination and they reported that the bowl was blackened and the needle pivot chipped, but with these exceptions the compass was serviceable. An exploration of the metal surrounding the compass revealed various magnetic poles in different parts of the structure which were very local, but two very pronounced red poles were found on the port side of the cockpit. These were due to the engine and radiator control rods which run in a casing outside the fuselage, and to the tail adjustment control chain which runs in another casing just above the engine controls. The forward end of the engine control rods had a very pronounced red pole which was situated immediately on the port side of the compass (the compass was on the port side of the machine) and not more than a foot away. These two red poles were quite sufficient to account for the excessive deviation of the compass."

Remarks.—This is one of the few cases of an aeroplane having been struck without a trailing aerial. It is impossible to be certain, but the indications all point to a side stroke from the main lightning discharge which passed very near to the aeroplane.

The unreliability of the compass before the machine was struck is unusual. It may have been due to electrical currents passing harmlessly and silently through the machine; but it was much more probably due to unsteady motion of the plane owing to turbulence.

The strong blast of air which came from the cabin through the little window behind the pilot's head into the cockpit was due to the violent local changes in pressure which accompany a lightning discharge and to which the thunder is due. A lightning discharge has really the nature of an explosion, the rapid heating of the air in the channel causes it to expand explosively. The passage of the explosion wave causes very marked differences of pressure within and without enclosed spaces, and it was this difference of pressure between the cabin and the cockpit which gave rise to the blast of air to which the pilot refers.

The misfiring of the engine may have been due to temporary interference with the permanent magnetic field of the magnetos, for there must have been some very large electrical currents passing through the metal parts of the machine to do the structural damage reported and to magnetise the control rods so as to put the compass permanently out of order.

IV—Aircraft (flying in Formation) struck by Lightning near New Alresford on April 8, 1927. (762312/27.)

First pilot's report.—"On April 8, 1927, I was leading a formation of three machines from Spittlegate to Gosport. When near New Alresford, east of Winchester, we flew into a heavy hailstorm.

"My wireless operator earthed the aerial, wound in the generator and put all switches at 'OFF.'

"When in the centre of the storm there was a loud explosion and what appeared to be a flash of flame struck the machine, extending from the engine to my cockpit. I felt no shock, but distinctly felt warmth, especially round my legs. I immediately throttled down my engine and glided out of the storm.

"As far as could be ascertained at the time the wireless gear was not affected in any way, but the compass acted in an erratic manner, pointing in any direction and never remaining steady.

"The machines flying on my right and left had closed up to me in the storm and distinctly heard the explosion and saw the flash.

"Upon a subsequent examination by the Squadron Air Pilotage Officer, the pilot's compass was found to have a deviation of approximately 120° when placed on north. The deviation varied considerably with movement of the control column backwards and forwards and movement of the aileron controls. The magnets in the corrector box were found to be serviceable. Upon testing the control cables and control chain actuated by the wheel on the control column, it was found that they strongly repelled a suspended magnetised needle held in their proximity.

"Further tests revealed the fact that the rudder control cables were similarly affected. Owing to the unsuitability of the apparatus available the tests were necessarily very crude and the investigations were incomplete.

"On examining the wireless instruments in this machine the wireless operator discovered the following damage due to the effects of the storm :—

(i) Main condenser on transmitter burnt out.
(ii) Tuning condenser on receiver shorting.

"Neither of the above instruments was in use at the time of the storm.

"I attach the reports of my wireless operator and the pilots of the other two machines."

Second pilot's report.—"At about 12.50 hours on the 8th instant, I was flying in close formation on the right of the flight of three machines. We were flying at about 1,500 feet through an intense hailstorm.

"For about 5 seconds I heard a loud crackling in my wireless headphones. This was followed by a flash of forked lightning which I saw. The flash seemed of considerable intensity and appeared to proceed from a point above and to the rear of the formation, downwards at an angle of 45° in the direction of the leader's machine. The discharge was accompanied simultaneously by a loud report.

"I did not see the lightning strike the leader as I was not looking at his machine."

Third pilot's report.—"Whilst flying in a formation of three machines from Spittlegate to Gosport, I flew on the port side of the formation leader.

"We approached and flew into an extraordinarily heavy hailstorm near Basingstoke. Visibility was very bad, and I flew as close as possible to the formation leader. While watching the leading machine, a vivid flame, accompanied with a loud report originated from the base of the pilot's cockpit. The flame spread over the entire vicinity of pilot's cockpit.

"I was approximately 30 yards away, and even though I had my wireless aerial out, experienced no effect."

Inspection report.—"Little information was obtained from the examination of the machine, the only sign of burning or blackening being on the woodwork carrying the aerial winch where the earthing wire was fastened. The earthing wire consisted of a piece of aerial wire about 8 inches long bonded to the machine; this wire was broken into three pieces after the discharge."

Remarks.—The following additional information was obtained. The three machines were in close "arrow-head" formation approximately 70 feet apart sideways and in line with the leader's rudder fore and aft. The heights relative to one another were approximately 6 feet above the leader. This example illustrates the local nature of a lightning discharge. The machines on each side experienced no ill effects in spite of being so near. The aerial of the machine struck was out but it was earthed. The earthing wire, however, was only a piece of aerial wire and, therefore, too thin. It fused and this no doubt was why the wireless apparatus experienced some small damage.

When a lightning discharge passes down an aerial there is a certain amount of side leak, therefore the maximum current is at the point where it joins the aeroplane. Normally this is where it fuses and the aerial falls off. The same happened in this case, except that the part which melted was the temporary connexion and therefore the aerial itself did not fall away.

The reports from the two side machines are interesting in showing how deceptive the apparent origin of a lightning flash can be. According to one report "a vivid flame, accompanied with a loud report, originated from the base of the pilot's cockpit. The flame spread over the entire vicinity of the pilot's cockpit," which might be interpreted to mean that the aeroplane was the cause of the flash, but the other report says "the flash seemed of considerable intensity and appeared to proceed from a point above and to the rear of the formation, downwards at an angle of 45° in the direction of the leader's machine." As stated above, it is impossible by visual observation to say where a lightning flash commences.

V—Passenger Aeroplane struck by Lightning on February 23, 1931. (92612/31.)

Report.—"The aeroplane was flying through a cloud when it was apparently struck by lightning. There was intense flash in the cockpit and the pilot experienced the sensation of a blow on the head which, however, did not have any ill effect.

"Examination of the aircraft after landing suggests that the flash entered the aircraft at the port navigation lamp and emerged at the aerial. The lamp bulb socket in the port navigation lamp has a fused hole about $\frac{3}{8}$ inch by $\frac{1}{4}$ inch, the wireless set is practically written off, the valves being blown and the back blown off the case, and the trailing aerial was fused and fell off.

"It is interesting to note that there were no signs of a thunderstorm at the time.

"The metal portions of the aircraft and notably the steel framework of the fuselage is so strongly magnetised that the compass is rendered useless."

Report of wireless inspection.—"On Monday, February 23, the wireless transmitter receiver fitted to this aircraft was seriously damaged and put out of action during a flight between Brussels and London, owing either to lightning or to the accumulation and sudden discharge of a static charge.

"From information received it appears that the pilot was flying in cloud and sleet at 2,500 feet, and owing to the noise in his telephones caused by atmospherics had switched off his set, thus "earthing" the aerial via the send-receive switch. He did not, however, reel in his aerial. Suddenly a flash occurred, appearing to emanate from beneath the dashboard, and later it was discovered that the W/T was out of action."

Remarks.—In this case the aerial was out but earthed. Little damage was done to the aeroplane but parts of the wireless set were destroyed. Damage of this kind is bound to happen if the aerial is connected to the set as well as earthed, for the electrical surge along the aerial must be communicated to the set as well as to the "earth," although its power of doing damage is insignificant in comparison with what it would be if the aerial were not earthed.

It is stated in the first report that there were no signs of a thunderstorm; on the other hand, in the second report it is stated that the atmospherics were so bad that the wireless set had to be switched off and the aeroplane was flying through sleet. These statements point to this being a case of an aeroplane flying into a region of high electrical force and initiating a lightning flash.

VI—Aircraft struck by Lightning near the Bell Rock (Scotland) on May 3, 1931. (119571/31.)

Pilot's report.—"The weather at the time was stormy, with frequent showers of heavy rain and hailstones; while flying on a compass course I passed into a very heavy hail-storm, at about 3,000 feet. Almost immediately there was a loud explosion which appeared to come from ahead of the aircraft, and at the same time a bright blue flash on a level with, and slightly to the left of, the propeller boss.

"I felt no sensation of electrical shock or physical discomfort of any kind. I at once shut the throttle and glided down to about 1,000 feet, when I opened up the engine again, and it picked up in a normal manner. After this the engine always seemed to run rough and vibrate on either magneto."

Wireless operator's report:—

"(i) *Weather conditions.*—Cloudy, stormy at intervals.

"(ii) *Distance from cloud.*—Flying through cloud.

"(iii) *Magnitude of flash.*—Momentary brilliant flash.

"(iv) *Sensation felt.*—Loud deafening bang in headphones. This occurred at the same time as the flash.

" (v) *Other observations.*—Passing through cloud and experienced noises in headphones like a rain storm, before I had time to reel in my aerial I perceived a momentary brilliant flash which seemed to travel along the gunwhale of the fuselage, from propeller to rudder. At the same time a flash occurred in the vicinity of the L.T. key. I went to switch on the transmitter and got a shock off the tumbler switch and then by accident touched the fuselage and got another shock. I reported to the pilot that the aircraft appeared to be electrically charged. Upon reeling in I found that the aerial weight and several feet of aerial wire were missing. Upon landing, the two centre blades of the L.T. key were found to be burnt through."

Remarks.—This is a typical case of a lightning stroke with the aerial out and not earthed. The shocks received when the wireless operator touched his instruments after the flash had occurred were not due to the aircraft retaining a residual charge from the lightning, but to the fact that the machine was still in a strong electrical field. The machine was found on inspection to be highly magnetised and had to be demagnetised, as described on p. 9, before the compass could be used.

VII—Aeroplane struck by Lightning near Whittlesey on April 21, 1932. (179673/32.)

Three aeroplanes flying in formation entered a storm with heavy hail. One of the machines was struck by lightning. The flash was very brilliant and momentarily blinded the pilot. The aerial was out but earthed. Slight damage was done to the propeller and parts of the fabric of the fuselage. The bonding was fused at three places and the aerial was fused at approximately one yard clear of the bell mouthpiece on fairlead. All wireless circuits were intact. The aeroplane was highly magnetised. There were no unusual features.

VIII—Passenger Aeroplane struck by Lightning on May 9, 1932. (92921/31.)

Pilot's report.—" I took off at 12.32 and climbed up into the cloud. At 12.35 I passed the usual wireless signal to my base station and received their acknowledgment. Atmospherics were noticeable. At 12.36 I notified the base station that my altitude was 2,000 feet.

" The base station acknowledged this and I understood that they had information for me regarding an aircraft approaching in my direction. Being unable to receive this message on my fixed aerial I ran out the trailing aerial. I then heard the base station commence to speak to me about another aircraft but the remainder of their speech was blotted out by atmospherics. I thereupon switched off the receiver.

" At this time I was flying at 2,000 feet in cloud on a steady compass course. Visibility was only a matter of several yards, the wing tips being invisible, and the windscreen wipers were unable to clear away soft snow which was falling and beginning to freeze on the windscreen. It was not unduly ' bumpy.'

" Approximately thirty seconds after I had switched off the wireless set, a deafening explosion occurred in the wireless behind me, and my seat was forced to the left of the control cabin, jumping the catch. I regained my position in front of the controls immediately and throttling back all engines, placed the aircraft in a gentle glide.

" Out of the corner of my eye I noticed a cloud of smoke clearing away, while fragments of glass were falling on my lap. An intense draught was rushing through the cockpit, and on calling to my assistant to shut the windows, I found that of the eight panes, five had disappeared and the starboard front pane was starred badly. The forward side pane on my side, which had been slightly open, was also badly cracked and slid right back.

" I told the assistant to look at the engines and see if any damage was visible outside. He reported that everything appeard O.K. outside the cockpit. I then opened up the engines gradually to 1,700 r.p.m. and no sign of any vibration was visible on either engines or aircraft. I also told the assistant to cut the trailing aerial adrift, but he replied that it had gone already.

" By this time my altitude was approximately 1,500 feet and I reckoned my position as being above Sevenoaks. I continued on the same course and still in cloud for another ten minutes, until I judged I should be over the lower ground east of Tonbridge, and then throttled back and descended to 500 feet, coming in sight of the ground at that height.

" In the meantime the assistant had examined the wireless compartment and found that the outside door was open with the small window blown out, and the communicating door to the forward cabin was blown in about 1 inch against the jamb, and jammed. The aerial winch was shattered and a fire extinguisher in two pieces."

Remarks.—Again the main trouble was in the wireless cockpit and was due to an unearthed aerial. The breaking of the windows and the jamming of the door were obviously due to violent changes of air pressure ; but it is impossible to say whether this was due to the disruptive effect of the electrical current conveyed into the wireless cabin by the aerial or whether it was due to the explosion wave of the main lightning discharge. The latter is the more probable because the large cabins of passenger aeroplanes, which are made almost airtight to keep out the draught and noise, react with great force to rapid change of outside pressure.

A similar account of structural damage in a large passenger aeroplane due to the explosion wave has already been given above (page 13). At the same time the shattering of the aerial winch shows that there was a large disruptive effect due to the electrical tension.

IX—Aeroplane struck by Lightning over the Irish Channel on June 17, 1932. (123273/31.)

Pilot's report.—" I was flying the aircraft at the time ; after leaving the Scotch coast at Portpatrick at about 14.55 hours, I sighted a line squall about half way across the channel, at right angles to the line of flight, extending on either hand as far as the eye could see. As I approached it I could see the sun shining on the other side of the squall. I had now climbed to 4,500 feet and was just below the base of the clouds.

" Upon entering the squall the visibility deteriorated due to heavy rain. A few seconds later I heard a violent explosion from the port side of the aircraft and turned immediately to look at the port engine. While in the act of turning my head, what appeared to me to be a ball of fire, about the size of a man's head, flashed by me. It appeared to pass between me and the port engine along the line of flight in the same direction as the aircraft was heading. It disappeared a little way ahead of the aircraft.

" I took a quick look at all my instruments and found everything in order. I felt no shock and the aircraft was under perfect control. I passed down a message inquiring as to what had happened and any damage done, and was informed that the W/T set had been seriously damaged, but that nobody was injured."

Wireless operator's report.—" When leaving the coast of Portpatrick, electrical interference became evident and I then commenced to inform Aldergrove that I was closing down temporarily and would call the station again later. I was sending this at about 15.04 hours. I had just pulled the telephone plug out in the middle of transmitting when, about 2 or 3 seconds later, a violent explosion occurred which completely wrecked the transmitter.

" I was dazzled by the flash for a few seconds and when I could see properly again I quickly disconnected all the accumulators and wound in the generator, as several leads were hanging loose and a danger of a short circuit thereby existed. I then surveyed the damage and found :—

(1) The aerial had fused and was lost.

(2) The fairlead was smashed.

(3) There were holes in the fabric in the side of the fuselage and by the wing root, where the aerial was led out.

(4) The wire had been blown off the aerial plug and also the connexion to the aerial terminal."

Remarks.—The only point which is unusual in this case is the remark of the pilot about the ball of fire. It is difficult to say how much of what he saw had objective reality. It is possible that what he saw was the end of the lightning channel as it bored its way through the air from the cloud to the ground. The whole question of the actual formation of a lightning channel and its connection with ball lightning, if any, is so vague that no statements can be made.

X—Passenger Aeroplane struck by Lightning near Patras on February 24, 1933. (245192/33.)

Pilot's report.—" I took off at 11.05 G.M.T. and I encountered good weather until at Patras there were signs of rain storms. Just about 15 miles east of Patras as 13.45 I was going round the edge of a heavy hailstorm at 1,500 feet when there was a blinding flash and a loud report.

" The control cabin instantly became full of smoke and fumes. When the smoke had cleared away I requested the assistant to make an examination of the ship. He reported all O.K. but the forward starboard roof panel in the saloon had been blown out and the passengers complained that a flash had come through it and passed out by the bilge cover.

"I would like to point out that with the exception of seeing some flash lightning in the distance over the Albanian hills, the only real fork lightning that I saw was that which struck me."

Wireless operator's report :—

"(1) Aerial was out at the time.

"(2) Aerial was earthed.

"(3) Headphones were not being worn.

"(4) Atmospherics were not particularly severe at the time, reception not being interfered with seriously. The type of atmospherics was 'crashers.'

"The damage was as follows :—

"(1) Aerial fused off about 3 inches from winch end.

"(2) Dexina tube scorched and insulation broken down, rendering it unserviceable.

"(3) Aerial reel scorched and insulation broken down.

"(4) Aerial ammeter completely fused up.

"(5) Contacts on barrel switch wave transmitter burnt and rendered temporarily unserviceable.

"(6) Drive valve burnt out.

"During bad weather or when atmospherics are severe the aerial is usually wound in but it will be appreciated that it is at this time that the W/T is required most. Weather reports and D.F. bearings are often required, it may also be necessary to fly low over a ship.'

Inspection report :—

"(1) A hole about the size of a penny was found in rear of the port upper wing tip in line with the navigation light. The hole was through the fabric and metal, the metal around the hole being fused.

"(2) The bottom of the hull (stainless steel) in line with the aerial, when trailing from the aerial lead into about 10 feet aft was slightly pitted. This was obviously caused by the fusing of the aerial.

"(3) No other damage occurred with the exception of the wireless set."

Remarks.—The chief points of interest in this case are that atmospherics were not particularly severe at the time and that the flash which struck the plane was the only one observed in the neighbourhood. This would indicate that the machine flew into a strong electric field and the long trailing aerial initiated the discharge.

APPENDIX II—PROTECTION OF AIRSHIPS FROM DAMAGE BY ELECTRICAL DISCHARGES

REPORT OF COMMITTEE

(488223/24.)

The relevant available evidence on the subject of the effect of electrical discharges on lighter than air craft is scanty.

A certain amount of information relating to captive balloons has been collected in the "Interim Report of the Committee for the Electrification of Balloons."*

A rigid airship is considered to be less liable to danger from electrical discharges than a kite balloon or a non-rigid airship owing to its metallic enveloping structure, and it has not been possible definitely to trace any properly authenticated cases of rigid airships having been destroyed under the effects of atmospheric electricity.

There are, however, a few practical precautions which can be taken, and which it is desired to emphasize. It is considered essential that all metal parts of the ship should be electrically bonded together. It has been reported that an attempt has been made in the case of one particular airship, to test the efficiency of bonding by insulating the hull of the ship and by passing high frequency discharges through it, before the gas bags or outer cover were inserted in the ship. It has been claimed that by this means it has been possible to detect in the darkness the presence of sparking and brush discharges, which were then obviated by employing special local bonding at the places where these phenomena were observed. This is considered to be a wise precaution and the adoption of this test is recommended wherever praticable.

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* London : Advisory Committee for Aeronautics. Special Committee on the Electrification of Balloons. Interim Report. February, 1919.

The suggestion has been made that where a projection of one member closely approaches the projection of another independent member, a high-frequency oscillating discharge may tend to jump across the small intervening air space between the two members, even although there is a continuous metallic path for the discharge through the ship. Any tendency of this kind should be revealed by the test recommended above.

Special precautions should be observed with regard to valves. The valves should be electrically bonded to their seats. The gas discharge hoods from the automatic valves should not be placed in a region likely to be struck by an electrical discharge, thus it would be better for these hoods to be situated in the centre of a panel, away from the metal girders, instead of close to the joints of these girders as is the present practice.

It has been reported on good authority that on several occasions electrical discharges have quite clearly been observed to strike a ship, to pass through the hull of the ship and out again. It is further reported that these discharges nearly always strike the ship on the top in the region of the front half and pass out again either from the control car or the forward power cars. It is, therefore, advisable for the gas discharge hoods to be situated in the back half of the ship as far as possible.

It is considered undesirable that any sharp projections should be fitted which will definitely invite sparking or brush discharge. There are certain projecting parts of the ship, however, which are more likely to invite electrical discharge than others, notably the nose, and the top fin. The latter will probably be particularly bad in this respect when the ship is riding at a mooring mast.

It is considered desirable that at such points as this, sufficient metal should be provided to carry the discharge into the body of the hull so as to avoid the risk of local fusing of the metallic parts.

It is impossible to give an estimate of the differences of potential which may be expected to occur between the two ends of the ship, but it may be pointed out that in the case of R.33 the total cross-sectional area of the longitudinal members (duralumin) is 8 square inches.

It is generally considered that it would be advisable for all fabrics used in a ship to be completely conductive and homogeneous from this point of view. At the same time, it is fully realised that this may be difficult, if not impossible, to achieve. Thus dopes containing metallic powders have been shown to possess a very low conductivity indeed, and the rubber adhesives which have been used in the preparation of a large number of gas bags are also of very good insulating material.

Experiments have shown that a deposit of moisture on the surface of an insulating fabric will provide a path for the passage of a discharge, and in cases where the external surface of the fabric is dry and the internal surface is wet, the discharge may even puncture the fabric and travel along the internal face. It is also possible where the fabric contains a layer of insulating material, that the potential of the inner face is different from that of the outer face, so that when the fabric is torn or pierced a spark may occur at the aperture.

For all these reasons it is considered that it would be preferable that gas bag fabric should not contain a layer of insulating material such as rubber.

Experiments are in progress to test the relative merits of various fabrics from this point of view. It is possible to say at the present moment, however, that fabrics with a gelatine-glue adhesive are superior to fabrics with a rubber adhesive from this point of view, and it is well known that considerable importance is attached to this point by German contractors.

The difficulties involved in making an outer cover which shall be homogeneously conducting are recognised, and it is considered possible that an electrical discharge in endeavouring to reach the metallic framework might cause damage in piercing the non-conducting cover.

It is therefore recommended that small flat metallic studs should be attached to the top girder of the ship and to the fins projecting through the fabric in order to avoid the danger just referred to.

It is probable that one of the most severe conditions to which an airship will be subjected from an electrical point of view, is when riding to a mooring mast. The ship should be effectively bonded to earth, and if the mooring mast is of ferro-concrete, special conductors will have to be provided.

It would also appear desirable to have a metallic conductor trailing from the tail of the ship and efficiently connected to earth, so that discharges which strike the top fin do not necessarily have to travel through the whole length of the ship in order to reach the earth.

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